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DEPARTMENT OF DEFENCE

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

AERONAUTICAL RESEARCH LABORATORIES

MELBOURNE, VICTORIA

STRUCTURES REPORT 380

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DOUGLAS J. SHERMAN

Approved for Public Release.

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WIND ENERGY—HOW RELIABLE?

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SUMMARY

The reliability of a wind energy system depends on the size of the propeller and the size of the back-up energy storage. Design of the optimum system for a given reliability level can be performed if a time series of wind speed data is available. However, a design based on conventional meteorological records, which sample the wind speed with a ten minute averaging time at three-hourly intervals, will over-estimate the storage by a factor of approximately 2, and if the wind speed is only available on a daily basis the storage will be over-estimated by a factor of 2·5 to 4·0. This is because a propeller can respond to wind speed changes in much less than ten minutes and also because three-hourly sampling does not often pick up the brief high-speed incidents which generate a significant part of the wind energy. A nomogram is presented, based on some continuous wind speed measurements, which enables storages calculated from three-hourly or daily data to be appropriately reduced because of these two effects.

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16. *ABSTRACT*

The reliability of a wind energy system depends on the size of the propeller and the size of the back-up energy storage. Design of the optimum system for a given reliability level can be performed if a time-series of wind speed data is available. However, a design based on conventional meteorological records, which sample the wind speed at three-hourly intervals, will over-estimate the storage by a factor of approximately 2, and if wind speed is only available on a daily basis the storage will be over-estimated by a factor of 2·5 to 4·0. This is because three-hourly sampling does not often pick up the brief high-speed incidents which generate a very large part of the wind energy. A nomogram is presented, based on some continuous wind speed measurements, which enables storages calculated from three-hourly or daily data to be appropriately reduced because of this effect.

CONTENTS

1. INTRODUCTION

The world shortage of fossil fuels and the consequent rise of interest in alternative methods of energy production have not touched Australia very deeply, since the known coal reserves should be adequate for its small population for some time to come. Nevertheless, the Australian Senate Standing Committee on National Resources[1] did conclude that "wind power does have a viable role for small scale applications in isolated locations where wind is a reliable energy source". A particular example of such a small-scale application has been suggested by Herrera *et al.*[2] This is the power supply for minor marine navigational aids mounted on buoys. Wind energy may also have a place in power supplies for buoys used to listen for the presence of submarines, and remote communications systems along southern parts of Australia's coastline which are often clouded over but which are subject to frequent gales.

The design of a wind power system to supply a given load demands a trade-off between the size of the wind generator and the size of the back-up energy storage. A generator that is bigger than necessary can supply the load at lower wind speeds, and so a reduction in the size (and cost) of the back-up energy storage is possible. In order to find the most economical system and to design the system for given reliability it is necessary to know the durations of lulls in the wind and the duration and frequency of the gusts. This information is very variable between different geographic regions.

The conventional meteorological data available in various countries is fairly similar, and a proposed standard is given by the WMO.[3] In Australia for example, the network consists of a small number of meteorological stations where the maximum wind gust each day and the 10-minute average wind speed at three-hourly intervals is recorded. There is also a much larger network where the 10-minute average wind speed is recorded at 9 a.m. and 3 p.m. each day. It will be demonstrated below that this set of data is of itself inadequate for the design of a wind power system because both the averaging period and the sampling interval are too great. However, it does include the necessary information for a climatic description of the winds at a given place. It is proposed here that one or two more detailed sets of wind speed data should be used to determine how the calculated storage requirement of a system varies with the averaging time and frequency of sampling of the wind speed. This micro-meteorological variation may be a function of the roughness and topography of the surrounding terrain, but otherwise is likely to be constant over large climatic regions. It could therefore be used to scale the storage requirements that would be calculated from the conventional meteorological record, available at any place.

Thomson[4] has recorded wind speed measurements at an anemometer mounted on a building at the ARL site during 1971 and early 1972. The wind speed was measured each second, with a miniature cup anemometer mounted 14 m above ground level. These measurements will be used to estimate for the Melbourne region how wind energy storage requirements vary with the frequency of data sampling.

2. THE WIND POWER FORMULA

In a wind with velocity V, the mass of air which flows through a unit area is

$$M = \rho V \tag{2.1}$$

where ρ is the air density. This air has a kinetic energy per unit time

$$P = 0{\cdot}5\, M V^2 = 0{\cdot}5\, \rho V^3 \tag{2.2}$$

Not all of this energy is recoverable, because the air downstream of the propeller must have a finite velocity for it to continue moving away from the propeller. Betz (see Wilson *et al.*[5]) has shown that the maximum power that can be delivered by an ideal wind machine of unit area is

$$P_{max} = (16/27)\,(0\cdot5\,\rho V^3) \qquad (2.3)$$

although even the best real machines attain little more than half the efficiency of this ideal machine. Because the power recovered is proportional to V^3 several consequences follow:

(*a*) A large part of the energy is involved in relatively few occasions when the wind speed is very high. However, the stronger occasional storms may be so scattered that it becomes uneconomic to store energy to carry over the full time interval between. It may be more economic to design a system which can provide the necessary capacity at a lower speed and allow energy to go to waste during the larger storms. In fact if a propeller is designed to operate at a moderate velocity, it may be preferable to feather the propeller during the storms rather than design it to withstand the large aerodynamic forces (which increase as V^2) caused by operating during the storm.

(*b*) The periods of high wind velocity which are important for wind power generation are usually fairly brief. A three-hour sampling interval may be so long that on many occasions the brief high-speed storms will not be sampled. If records of sufficient length are available then a true histogram of 10-minute average wind speeds at any given time of day will be obtained, but the necessary record lengths may be quite excessive.

(*c*) It is important that an appropriate averaging time be chosen when measurements of wind speed are made. For an interval during which the velocity varies, the mean of the cube of the velocity is far greater than the cube of the mean velocity. The appropriate averaging time depends on the response characteristics of the wind machine, but it can be quite small. Small size generators may operate at variable speed so that the response time is governed by the inertia of the propeller which controls how fast the propeller may speed up or slow down in response to a wind speed change. Larger wind machines generally operate at synchronous speed and use variable pitch propellers to optimise the power recovered from the wind. In this case the response time is governed by both the rate of change of pitch of the propeller, and the rate of build-up of lift in response to pitch and wind speed changes. The lift build-up is governed by the Wagner and Kuessner functions and is practically complete when about five chord lengths of the propeller cross-section have flowed past. With a chord of 2 m and a wind speed of 10 m/s this suggests a response time of one second. The response of a hydraulic actuator changing the pitch would be of the order of 10 milliseconds so it is the lift build-up which governs this case. The smaller variable-speed machine may have a slightly longer time of response, but because the machine is smaller the response time will not be very much greater. A one-second value therefore seems to be a suitable though slightly conservative figure to choose for the velocity averaging time.

(*d*) Many practical wind machines will not operate below some starting velocity around 5 knots. Although the wind speed is below 5 kn for quite considerable periods of time, not much energy is involved at these low speeds, so starting velocities up to around 5 kn have very little effect on the power available.

3. THE STORAGE PROBLEM

The problem of estimating the energy storage needed when a fluctuating energy input is required to supply a specified energy demand[†] is precisely analogous to the problem of calculating the reservoir capacity required when a fluctuating river flow is required to meet a given water demand. The method of analysis adopted here for the energy problem is the same as the "mass curve" method used for the reservoir problem. Figure 1 is a graph of six minute average wind speed with time, using Thomson's[3] ART data. Using the one second average values, the power entering a one square metre area wind machine was calculated using Equation (2.2) and graphed in Figure 2. The very spiky intermittent nature of a wind power supply is clearly visible. Figure 3 is the time integral of the graph in Figure 2. This curve is the analogue of the "mass curve" for river flow, and represents the total energy generated from time $t = 0$ up to any given time. The gaps in the curve represent gaps in the data, and during such gaps a rate of power generation

[†] For simplicity a constant energy or base load requirement is assumed.

somewhat less than the average power generation rate has been assumed. The way in which the mass curve is used to estimate the required storage volume is as follows:

Consider one of the "high points" of the mass curve such as P or Q in Figure 4. Assume that at this point the storage is full. From the high point considered lay off a sloping tangent with a slope equal to the demand rate on the system. At any later point t', the distance, s, represents the amount by which the demand has exceeded the supply during the time interval from the point P or Q up to time t'. In other words it is the amount by which the storage has been depleted. The maximum of all the possible intervals, s, is the storage capacity that is required in the system.

The mass curve procedure may be used simply to determine the maximum storage needed over a particular time. However, in some circumstances, it may be more useful to consider a modified procedure. For example a small system may need a very large storage to ensure that power is always available, but it may be acceptable to have a smaller (and cheaper) storage that will sometimes be unable to supply the energy demand for short periods. In this context we will introduce the concept of the reliability of the total system which we here define as the fraction of time for which a power system will be able to supply its design load.† The parameters affecting the reliability of a wind energy system will be the size of the propeller, the aerodynamic, mechanical and electrical efficiencies of the equipment, the size of the energy storage and the design load. The number of variables may be reduced by considering a propeller of unit area and equipment of 100% efficiency. (The method of dealing with non-ideal equipment is indicated by an example in the Appendix.) For a given wind record the average power P_a, generated will be used as a scaling parameter. To obviate seasonal variations P_a will be taken as the annual average power generation rate, which for Thomson's[3] ARL data is 71 W m^{-2}. When records covering several years are involved there is a considerable variation from year to year in the average power and in such cases P_a will be defined as the median value of the annual average power generation rate. The demand (or design load), D, of a wind energy system will be expressed as a fraction of P_a and the storage capacity, c, of the system will be expressed in days for which the design load can be supplied. Consider three systems with demands, D, of P_a, $0{\cdot}7\,P_a$ and $0{\cdot}5\,P_a$ respectively, and storages of 100 days for each system. (In terms of actual energy stored the three storages will be $100*24*3600*(P_a, 0{\cdot}7\,P_a, 0{\cdot}5\,P_a)$ Joules respectively.) For each such system with a fixed demand rate and a fixed storage capacity, a simulation of the state of charge of the storage at successive instants is carried out. If the power production at time t is $P(t)$, the amount of energy taken from the storage during a time intervale, Δt, is

$$\Delta s = (D - P(t))\,\Delta t$$

The symbol s denotes the amount of storage which has been called upon at time t. In the simulations reported here it is assumed that the energy storage is initially full so that $s = 0$. Increments in s are added to the initial state provided that s does not exceed the storage capacity, c, of the system and provided that s can never be negative (i.e. the storage can never be more than full). If the storage becomes empty ($s = c$) the total time for which it remains empty is recorded to be used in the calculation of reliability (or fraction of time for which the storage is not empty).

Figure 5*a* shows, for the several different possible demand rates, the variation of storage called upon, s, with time. The various demand rates for the curves shown have been labelled as P_a, $0{\cdot}7\,P_a$ and $0{\cdot}5\,P_a$. The storage called upon is expressed as a fraction of 100 days' storage for the respective demand rate, i.e. as a fraction of the accumulated energy consumption over 100 days.

When three-hour sampling of wind speed data is used, the rate of wind power production appears to be a more scattered process than it really is. As a result the calculated energy storage requirement may be greater than is actually necessary. Figure 5*b* shows the curves of storage called upon with time if the wind speed used to calculate the energy input is, during each synoptic

† In practice reliability will depend on time lost due to mechanical and electrical failures of equipment as well as time lost due to storage exhaustion, but equipment failures will not be considered in this study.

three-hour period, the six-minute average value at the beginning of that period. The peak storage requirement is up to twice that required when the second-by-second wind speed measurements are used.

4. FREQUENCY ANALYSIS OF WIND POWER GENERATION RATE

Figure 6 shows two probability distribution functions for wind power generation rate at the ARL site. The upper curve is for wind power calculated from one-second average values of wind speed, and the lower curve is for wind power calculated from six-minute average wind speeds. A six-minute averaging period (which is similar to the 10-minute average used for standard meteorological observations) underestimates the power available to a wind power system by 60% at the mean power production rate of $P_a = 71$ W m^{-2}. The histograms also emphasise the very intermittent nature of the wind power generation process. For 50% of the time the power available is less than 20 W m^{-2}, but for 10% of the time the power exceeds 180 W m^{-2}.

5. RELIABILITY DIAGRAMS AND THE EFFECT OF USING THREE-HOURLY SAMPLING OF WIND SPEED DATA

The calculations giving rise to Figures 5*a* and 5*b* are applicable to the case where it is possible for the system to be exhausted for small periods of time, but in this particular case (for the 100-day storage capacity) exhaustion did not occur. We will now consider a large number of wind energy systems with design loads ranging from 0·1 P_a to P_a and storages ranging from one day to 100 days. From the wind speed record it is possible to calculate the fraction of time for which the storage of each system would be discharged. Figures 7*a* and 7*b* show the fraction of time the system is unserviceable, due to storage exhaustion, for the cases of continuous sampling of the data and of three-hourly sampling respectively. For given levels of reliability the storage calculated using three-hourly sampled data appears to be 1·5 to 2·0 times what is actually required. The higher the power demand the greater is the over-estimate of the storage requirement.

6. EFFECT OF 24-HOUR SAMPLING

At many stations wind speed measurements are only available for limited times of day, in many cases at 9 a.m. and 3 p.m. D. M. Lee (personal communication) has observed that for many areas in Australia the annual probability distribution of the wind speed measured at 9 a.m. is very similar to the annual probability distribution of wind speed measured at all hours of the day, although there is some variation on a seasonal basis. If the hypothesis that 9 a.m. winds are representative of daily average winds is used, then it will be necessary to make estimates of energy storage based on a 24-hour data sampling interval. Thomson's[3] data cover only a year or so, which is insufficient data to relate a 24-hour sampling frequency to a second-by-second frequency. Instead we have analysed data for nearby Laverton, covering the period 1946 to 1978. The data is incomplete in that during some years wind speeds were not measured at certain times of day. In these cases the previous wind speed reading was assumed to continue for the period covered by the missing reading. Figures 8*a* and 8*b* show graphs of storage called on if power input is calculated for a three-hour sampling interval and for a 24-hour sampling interval respectively. In these graphs the top curve shows truncation, indicating exhaustion of the 100-day storage for significant periods of time. The graphs showing fraction of time power is unavailable (i.e. 1·0 − reliability) are shown in Figure 9*a* for data sampled three-hourly and in Figure 9*b* for data sampled only at 9 a.m. each day. Using 24-hour sampling the storage requirement for a given reliability is over-estimated (by comparison with requirements calculated from three-hour sampling) by 25% in the case of the larger storage capacities and by up to 100% in the case of the smaller storage capacities.

7. VARIATION WITH SEASON AND TIME OF DAY

Wind speeds have a very strong variation with time of day. This diurnal variation may be very important in wind power grids which cover a large area in order to average out wind fluctuations. Otherwise it would appear to be unimportant in the estimation of storage capacity because energy storages are almost always reckoned in capacities of days or weeks rather than hours. The average daily power production is all we need to know. However, if we try to estimate this daily production from available meteorological records we meet the problem that at many stations the wind speed has only been recorded at selected times of day, usually during daylight hours. If we do not use Lee's hypothesis we need factors which enable us to estimate daily average wind power production from observations at selected times of day.

Wind speed records have been obtained for a number of stations in Australia (see map in Fig. 15). The average wind speed, S, and average power production, P (Equation (2.2)), have been computed for each time of day for which observations have been made. There is a significant stochastic variation from year to year in the mean power generated, so for each year the values corresponding to specific times of day have been divided by the overall mean wind speed or power at 9 a.m. each day for that year. Then these normalised estimates of wind speed and power have been averaged for all available years. The variation of the whole year average wind speed and power with time of day is shown in Figure 10. Clearly the diurnal variation is very similar within each pair of nearby stations (Melbourne, Laverton) and (Archerfield, Eagle Farm). The high peak at about 3 p.m. or 4 p.m. in the subtropical region where Archerfield and Eagle Farm are situated correlates with the peak in thunderstorm incidence. The seasonal variation shown in Figure 11 is less clear, and may be complicated by the fact that the samples

Periods for which Data is Available

Region	Station	Dates	P_a (W m^{-2})
South Australia south-east coast	Robe	1957–78	190
Melbourne	ARL	January '71–March '72	71
Melbourne	Melbourne RO	1955–78	65
Melbourne	Laverton	1946–78	155
Brisbane	Archerfield	1939–49	42
Brisbane	Eagle Farm	1950–78	42

cover different time periods. The variation between nearby stations is considerable and any uniform variation with season is difficult to discern. Perhaps there is a tendency for winds generally to be slightly lighter in March–April and slightly stronger in October–November, and perhaps in January the winds at the subtropical stations of Archerfield and Eagle Farm tend to be relatively stronger than those at the more southerly stations of Melbourne and Laverton. Otherwise the variations between even close stations suggest topographical factors such as funnelling or shielding of winds that come from preferred directions at various times of the year.

The seasonal variation in expected power production is highly significant because many of the smaller wind power installations use a storage corresponding to about a week's to a month's demand. If at a certain site the expected power production in February (say) is significantly lower than the annual expected power, then design may need to be based on the lower figure. This may be a very significant factor. Figure 11 shows that on a yearly basis far more power is available at Robe than at Laverton. But if the lowest monthly power production governs the design Laverton is better off than Robe.

8. VARIATIONS FROM YEAR TO YEAR

Figure 12 shows the variation in the annual average power production rate based on the 9 a.m. wind speed observation. As with rainfall the year to year variability is quite large. In general the lowest yearly average observed is about half the median value. The only case of nearby simultaneous measurements is that of Laverton and Melbourne. The year to year variations have similarities but not nearly as much as might be expected. This may be because the Melbourne anemometer is situated near the central city in a place where many tall buildings have been erected over the past few years, causing a superimposed downwards trend on the graph.

9. CONCLUSIONS AND DISCUSSION

Conventional wind speed measurements at meteorological stations are only available at three-hourly intervals. At many stations they are not available even this often. Moreover, the wind speed averaging time of 10 minutes is much greater than is appropriate for a wind energy conversion system. If the sampled data is used to calculate the energy storage required by a wind power system the storage will be over-estimated. For the Melbourne region it has been shown that if three-hourly data is used in calculations the storage estimated will be about twice what is actually required for a given reliability. If wind measurements taken daily (at 9 a.m.) are used then the estimated storage will be about 2·5 to 4·0 times what is actually required. Figure 13 gives a pair of graphs which enable the correct storage capacity to be estimated from calculations based on three-hourly or daily wind speed data. These graphs are applicable to the Melbourne region and have been derived from Figures 7 and 9 by pairing storages required for each given demand at specified reliability levels.

System design curves such as those shown in Figure 9 are only valid for a particular site. It is of interest to see how much scatter occurs for different sites. Figure 14 shows some families of design curves, and the scatter is quite considerable, although a large part of the scatter can be logically explained. The curve for Melbourne Regional Office has not been presented because of the artificial effect of trend due to nearby building construction. The design curves for the two stations with the longest records (Eagle Farm and Laverton) are fairly close together — estimated storages generally differ by a factor of less than 2. This is quite interesting as the two stations are in quite different meteorological areas. For demands less than P_a, the curves for Robe show much greater reliability of the wind over short periods, and for long periods approach the curves for Eagle Farm and Laverton. Robe is situated on the exposed south-eastern coast of South Australia in a region of steady westerly winds, and so this greater reliability is to be expected. The curves for Archerfield seem the odd ones. However, only 10 years' data are available for Archerfield, and for short storage periods the curves are fairly close to the main two stations of Laverton and Eagle Farm. The departures for the long storage periods are probably due to the short record. In 10 years there are only 70 independent periods of 50 days, so fractions of time (for which power is unavailable) around 1% must have a large possible error.

An example of the practical use of the design curves is given in the Appendix.

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APPENDIX

A Practical Example

Herrera *et al.*[2] give several pieces of information which we will use below in an assessment of the storage requirement of a wind power system for a site near the Laverton anemometer.

(1) With a high-speed propeller an efficiency of 40% can be achieved.

(2) The Davey Dunlite Electrical Company of Adelaide manufactures wind powered generators. For several of their models the propeller diameter is 3·29 m. and this size will be used in the example below.

(3) Although the information is not given by Herrera *et al.*[2] we will assume that 25% of energy is lost during charging of batteries and another 25% during discharge.

The area of the propeller is 8·5 m². Using the Laverton data, P_a = 155 W m⁻² and the average wind power passing through the propeller is 1317 W. With an efficiency of 40%, 526 W will be converted into electrical energy. If we assume that all this energy is first stored in the battery and then used later, 25% of the energy will be lost during charging, and 25% during discharging, giving an average available power of 263 W. Using Figure 9*a* the storage capacity needed was determined for demands equal to various fractions of the available 263 W and for reliability at the 90% and 99% levels (see Table A1). Then using Figure 13 these storage capacities were reduced to allow for the sampling interval effect.

The designs shown in Table A1 differ from the usual design in that rather than finding the most economical system to supply a given demand, Table A1 is rather arranged to show the most economical storage demand combination that a given wind generator can supply. Columns 1 and 2 list various demands as a fraction of P_a (column 1) or absolutely in watts (column 2). The storage requirement that would be calculated using standard three-hour meteorological data is shown in column 3 and column 4 shows the storage required after the correction for the effects of averaging time and sampling interval is applied. The last column of the Table shows the actual size of the storage required in watt-hours for the given demand. Logically there would be another part to the Table in which the total cost per watt of demand would be calculated. This has not been included because prices of storage and propellers vary from time to time. However, using prices quoted by Herrera *et al.*[2] of about 10 cents per watt-hour for storage and $3000 for a generator and tower, the most economical system for 90% reliability supplies a demand of 0·7 P_a and has a capital cost of $25 per watt, and for 99% reliability supplies a demand of 0·3 P_a and costs about $50 per watt.

TABLE A1

Demand		Storage required		
		3-hr data	Continuous data	
D/P_a	Watt	Days	Days	Watt-hr
(a) Reliability 90%				
1·0	263	40·0	22·0	138,864
0·7	184	6·5	3·5	15,456
0·5	131	3·1	1·8	5,659
0·3	79	1·7	1·0	1,896
0·2	53	1·2	0·9	1,145
0·1	26	0·7	0·5	312
(b) Reliability 99%				
1·0	263	>100·0		
0·7	184	48·0	32·0	141,312
0·5	131	18·0	12·0	37,728
0·3	79	7·6	5·3	10,049
0·2	53	5·3	3·9	4,961
0·1	26	3·4	2·6	2,122

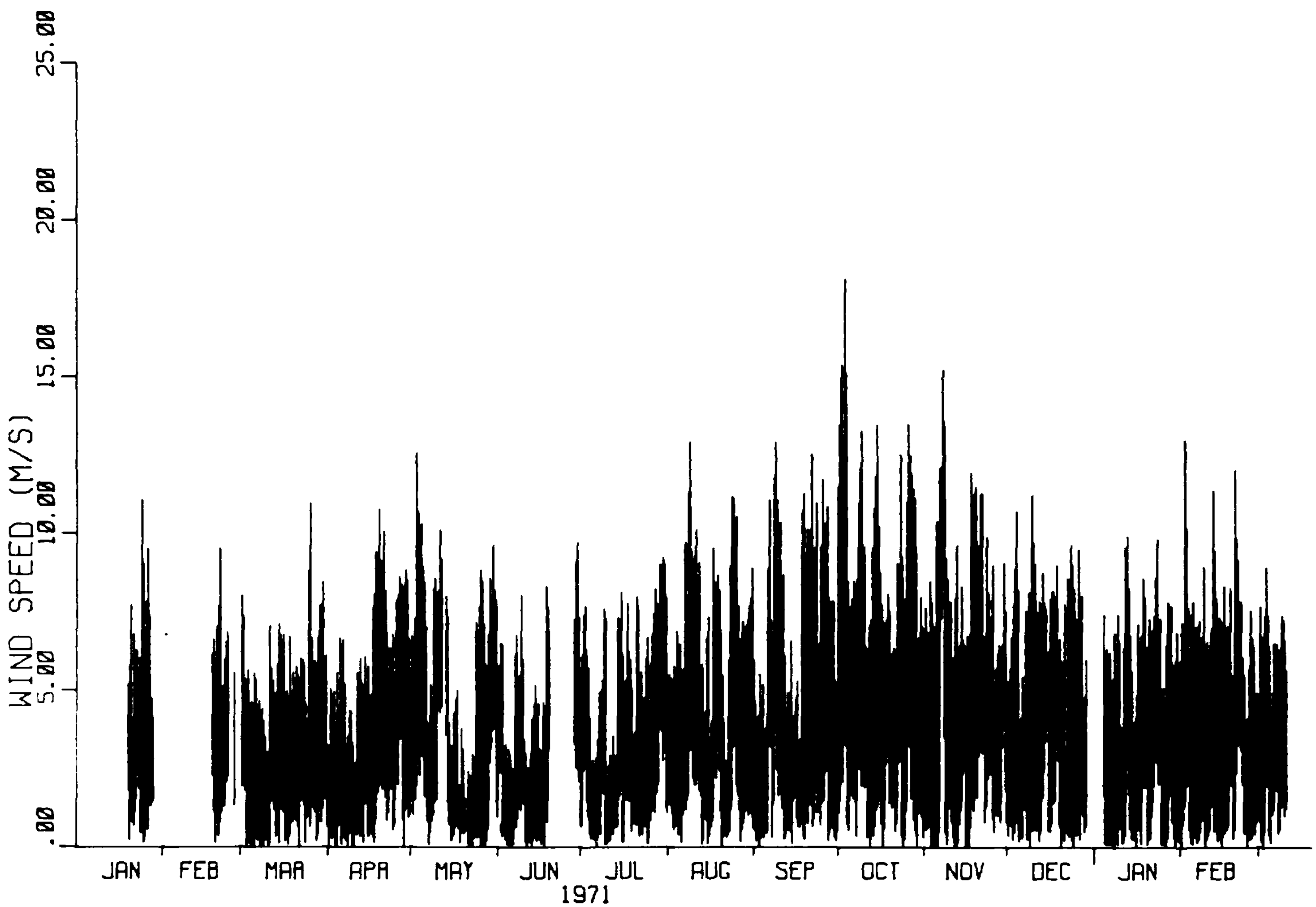

FIG 1: TIME HISTORY OF WIND SPEED AT ARL. (THOMSON'S DATA, 6-MINUTE AVERAGING TIME.)

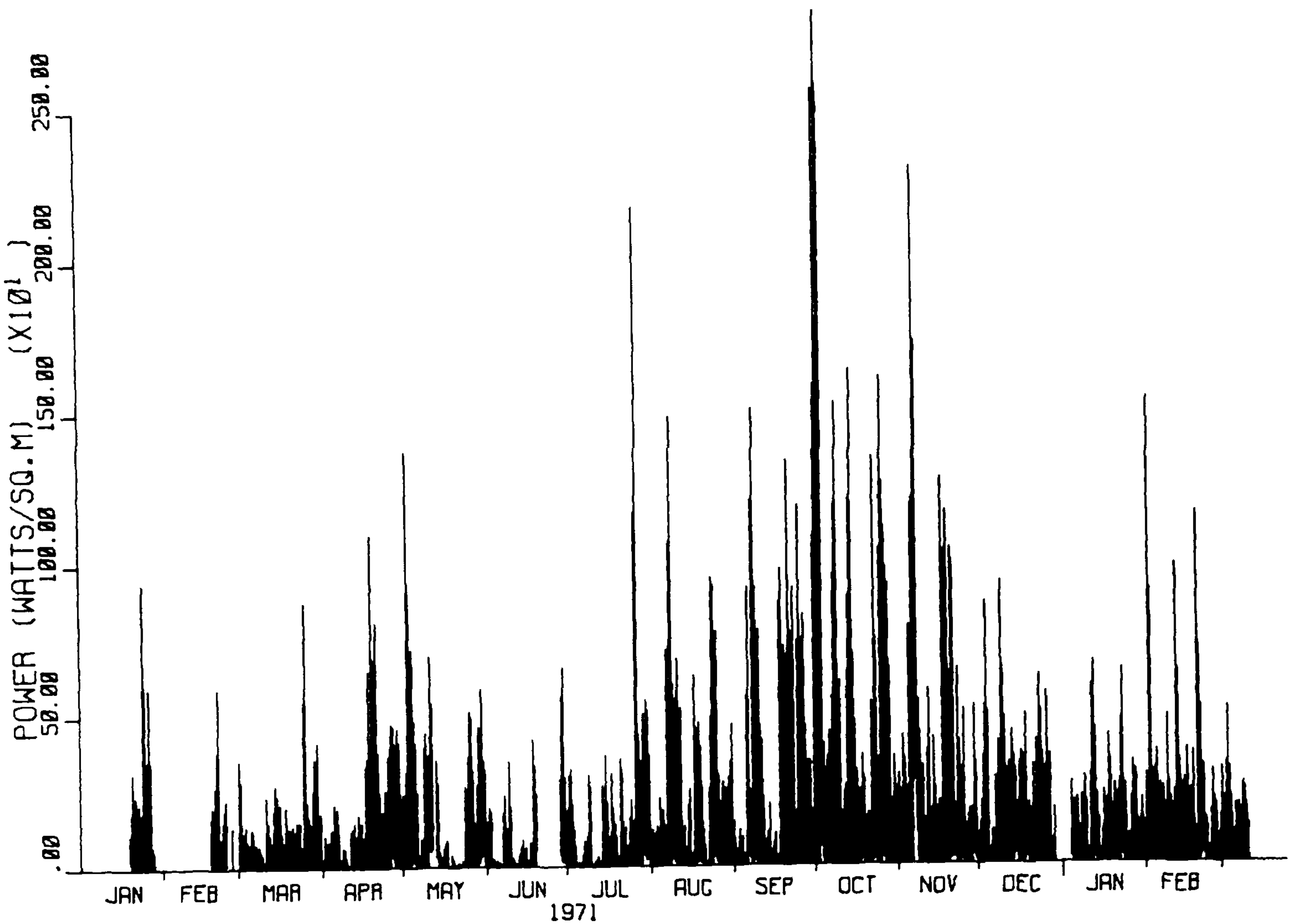

FIG 2: TIME HISTORY OF WIND POWER AT ARL. (THOMSON'S DATA, 1-SECOND AVERAGING TIME.)

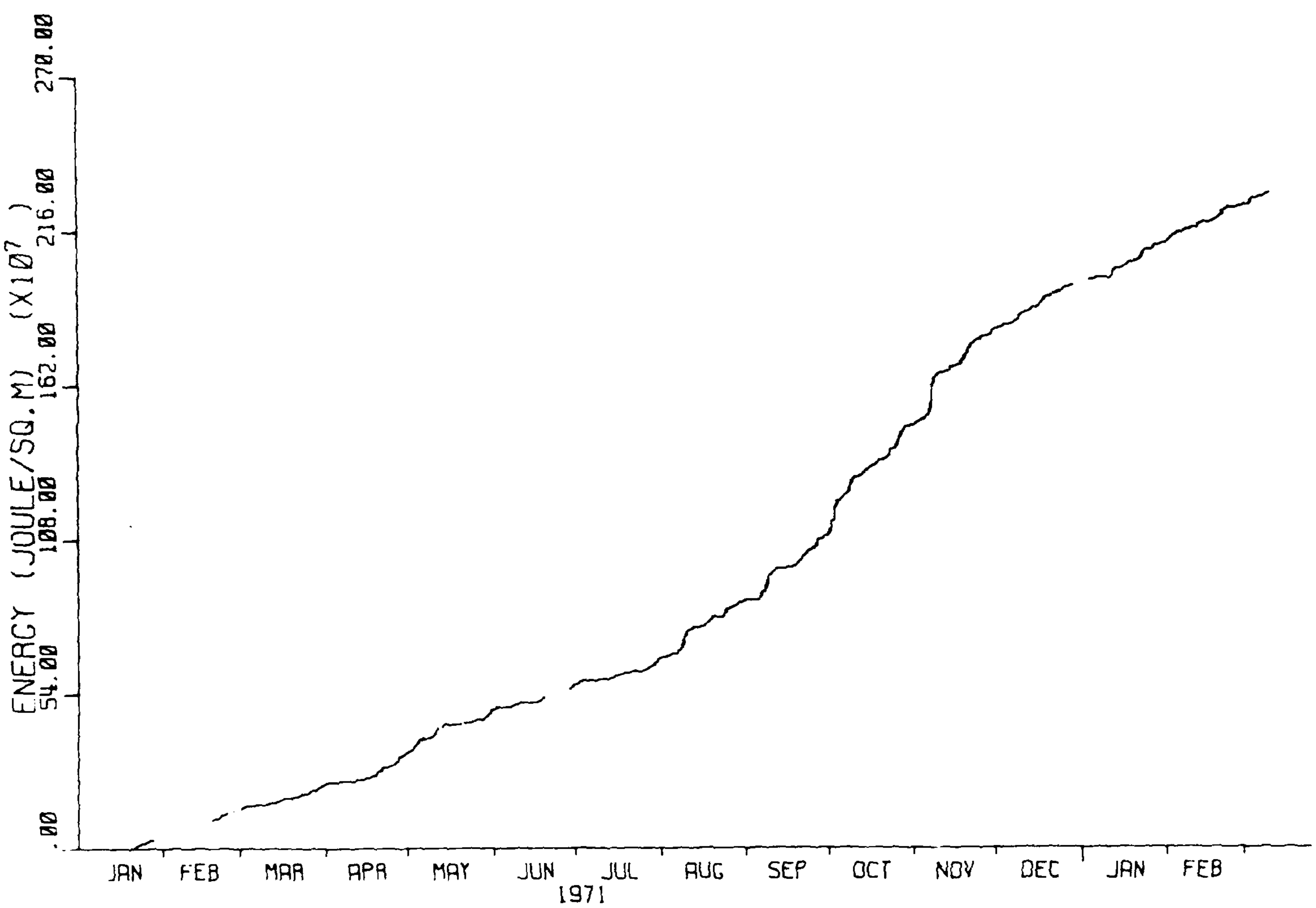

FIG 3: ACCUMULATED WIND ENERGY SINCE START OF RECORDING AT ARL.

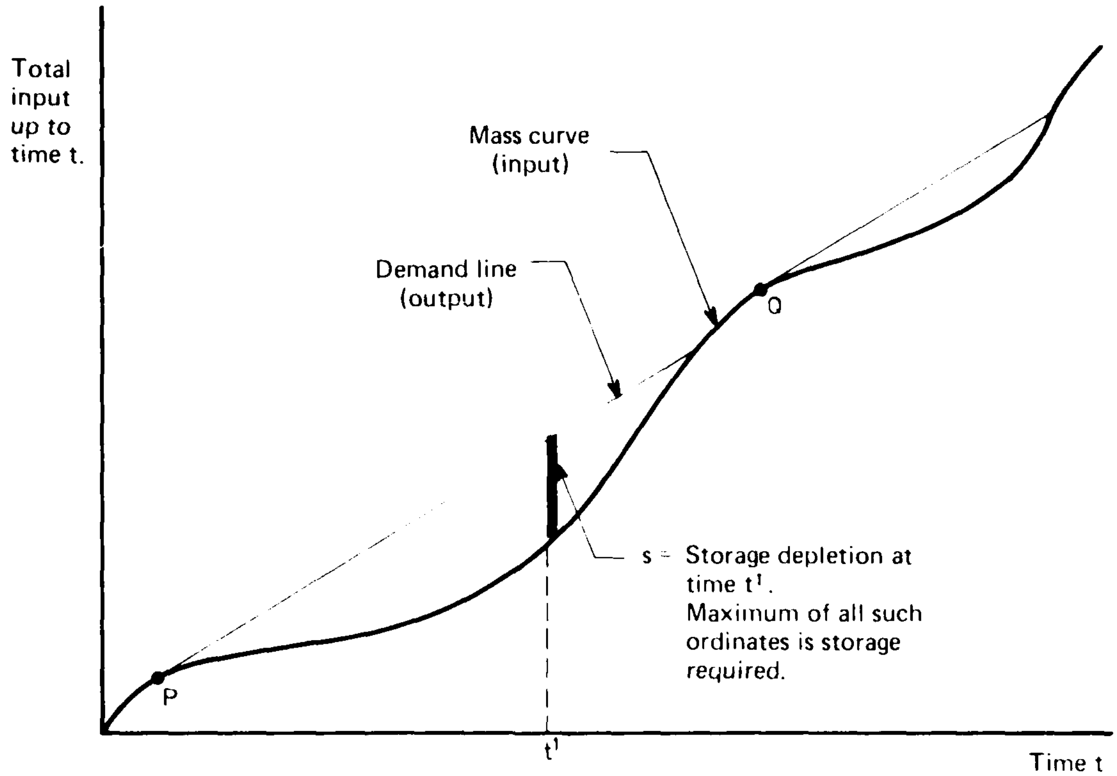

FIG 4: DERIVATION OF STORAGE REQUIREMENT FROM A "MASS CURVE".

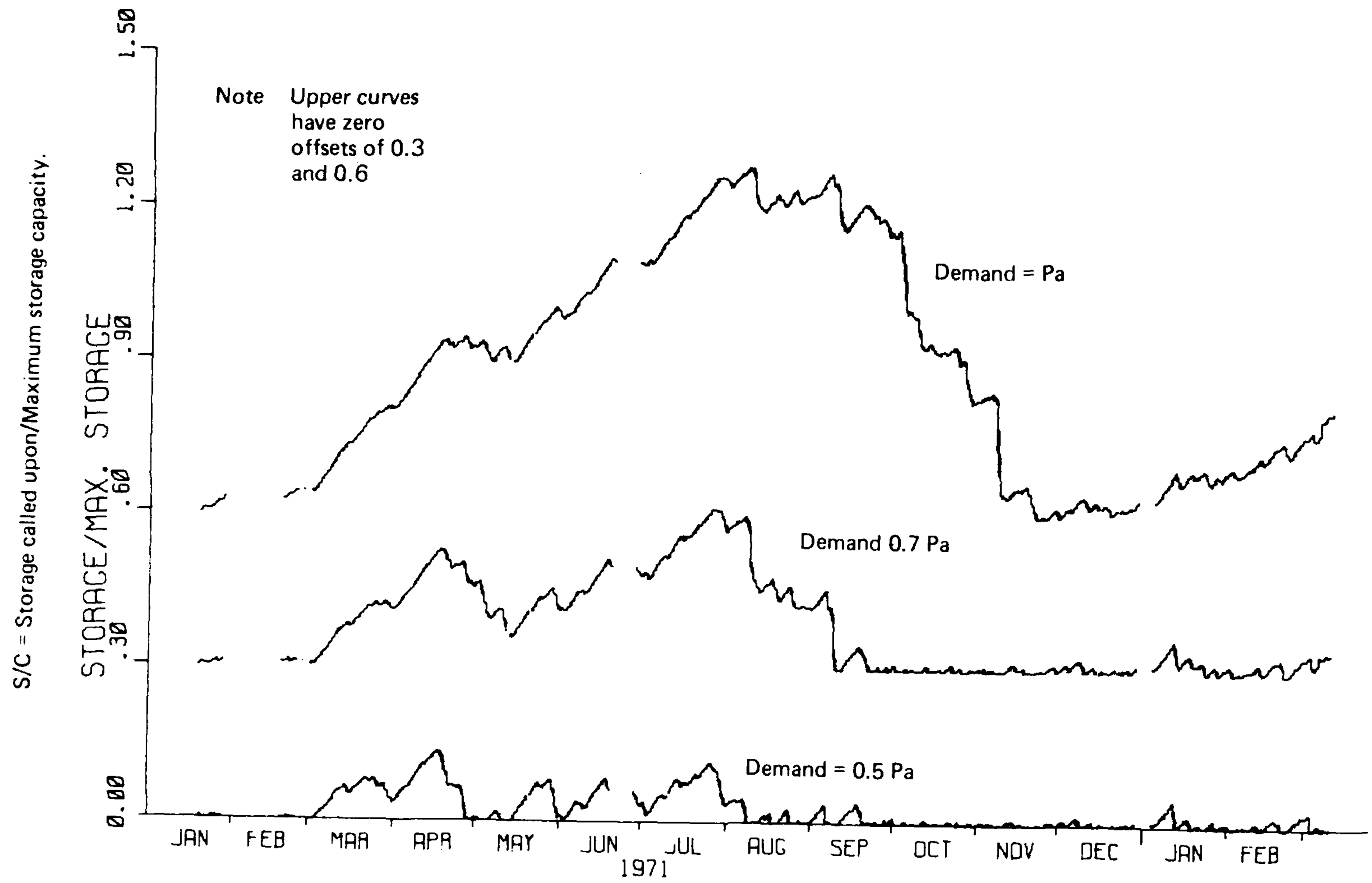

FIG 5(a): VARIATION OF ENERGY STORAGE CALLED UPON WITH TIME. CALCULATED USING CONTINUOUS ARL WIND SPEED DATA.

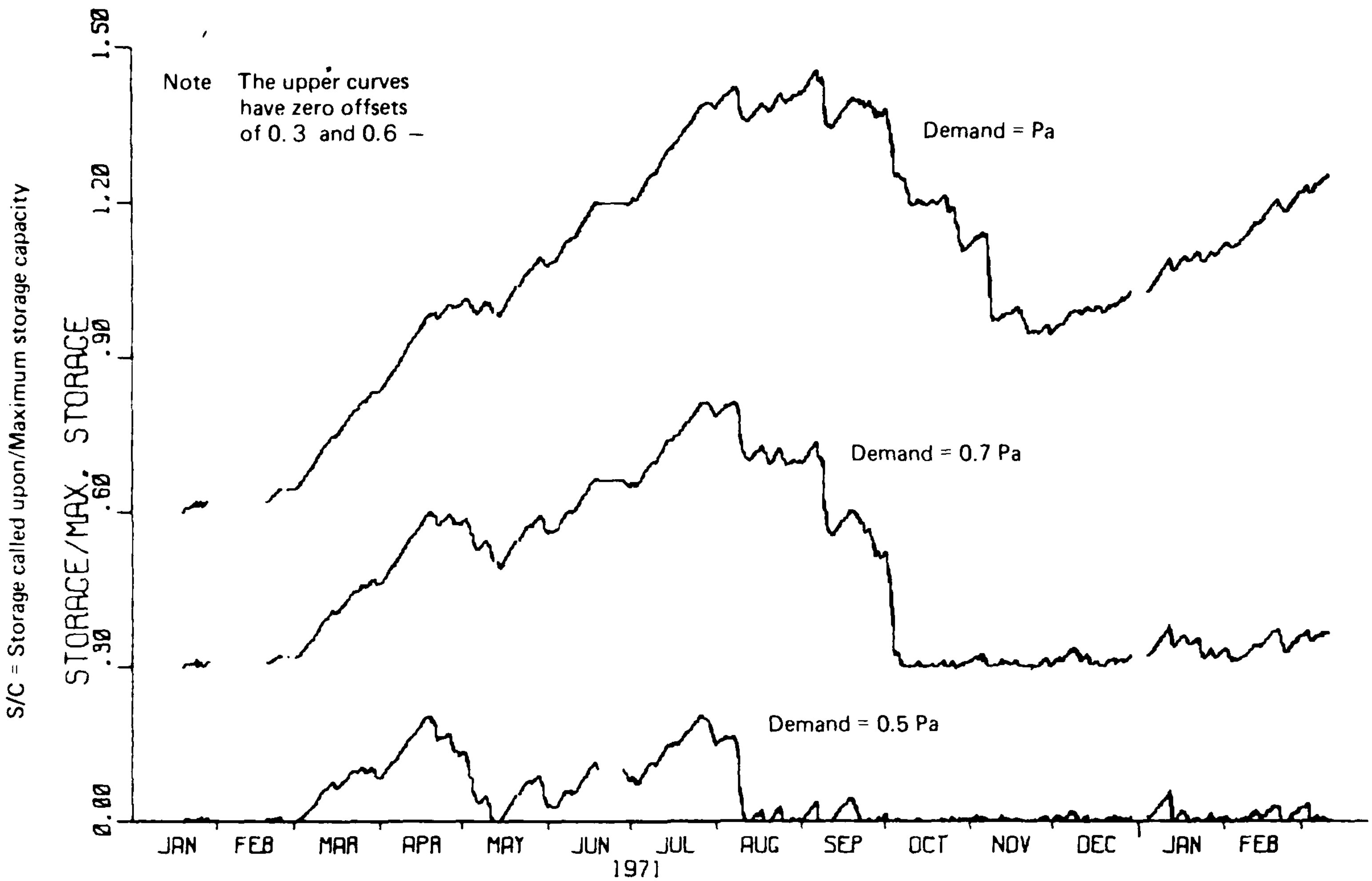

FIG 5(b): VARIATION OF ENERGY STORAGE CALLED UPON WITH TIME. CALCULATED USING ARL WIND SPEED DATA, AVERAGED OVER 6 MINUTES AND SAMPLED AT 3 HOURLY INTERVALS.

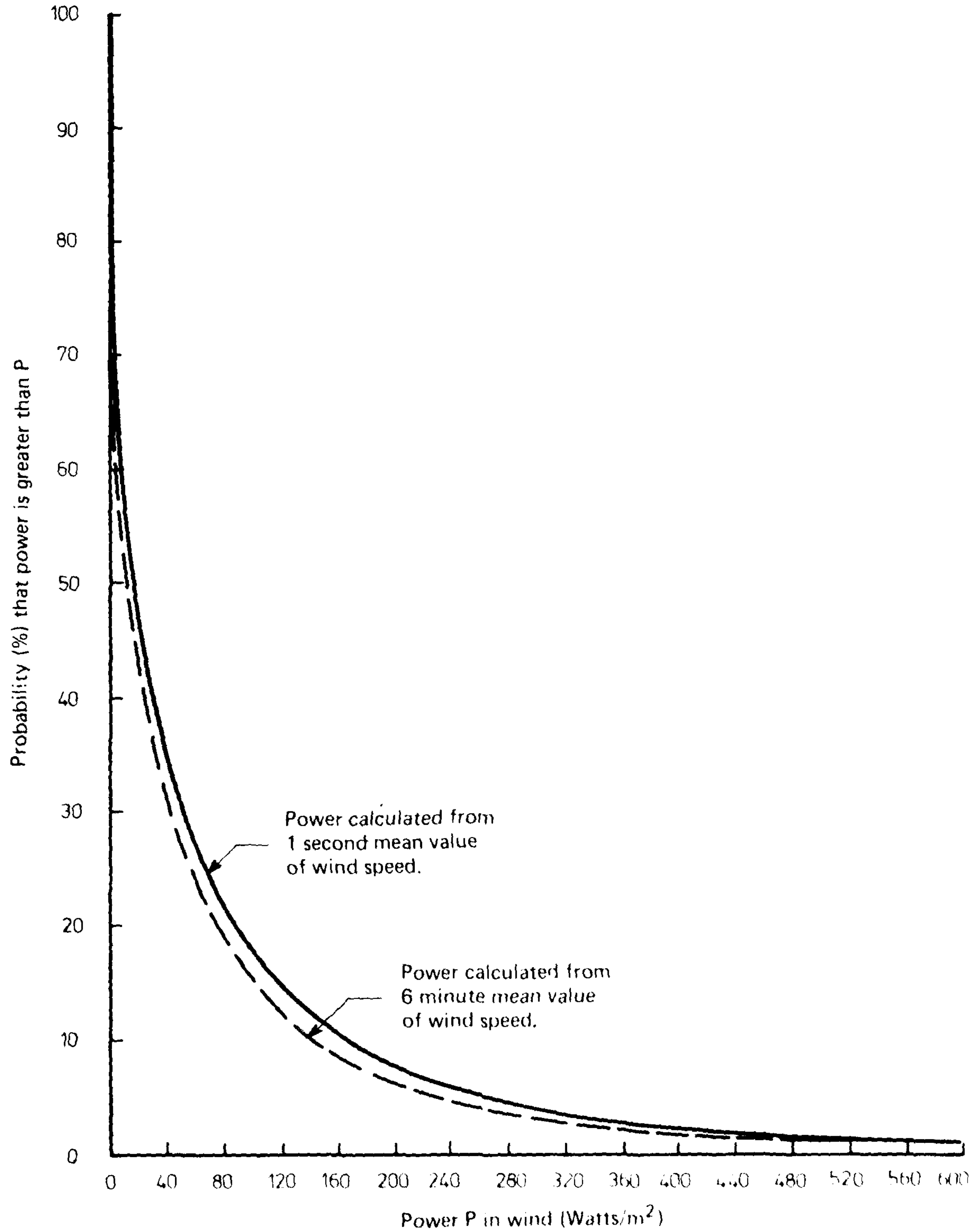

FIG 6: PROBABILITY DISTRIBUTION FUNCTIONS FOR WIND POWER, CALCULATED WITH 1 SECOND AND 6 MINUTE AVERAGING TIMES.

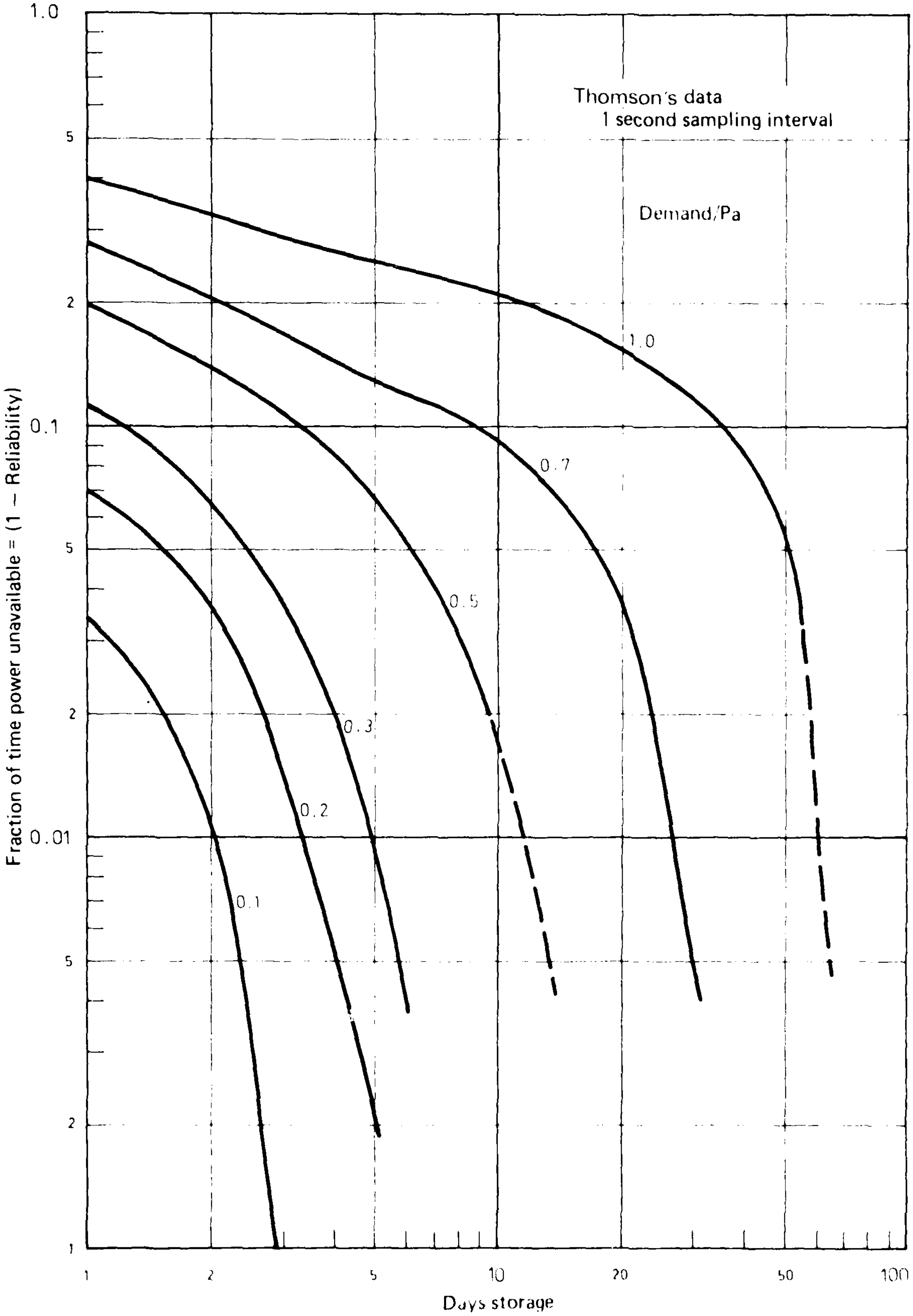

FIG 7a: RELIABILITY OF WIND POWER SYSTEMS WITH VARIOUS LOADS AND STORAGE CAPACITIES, CALCULATED USING CONTINUOUS ARL WIND SPEED DATA.

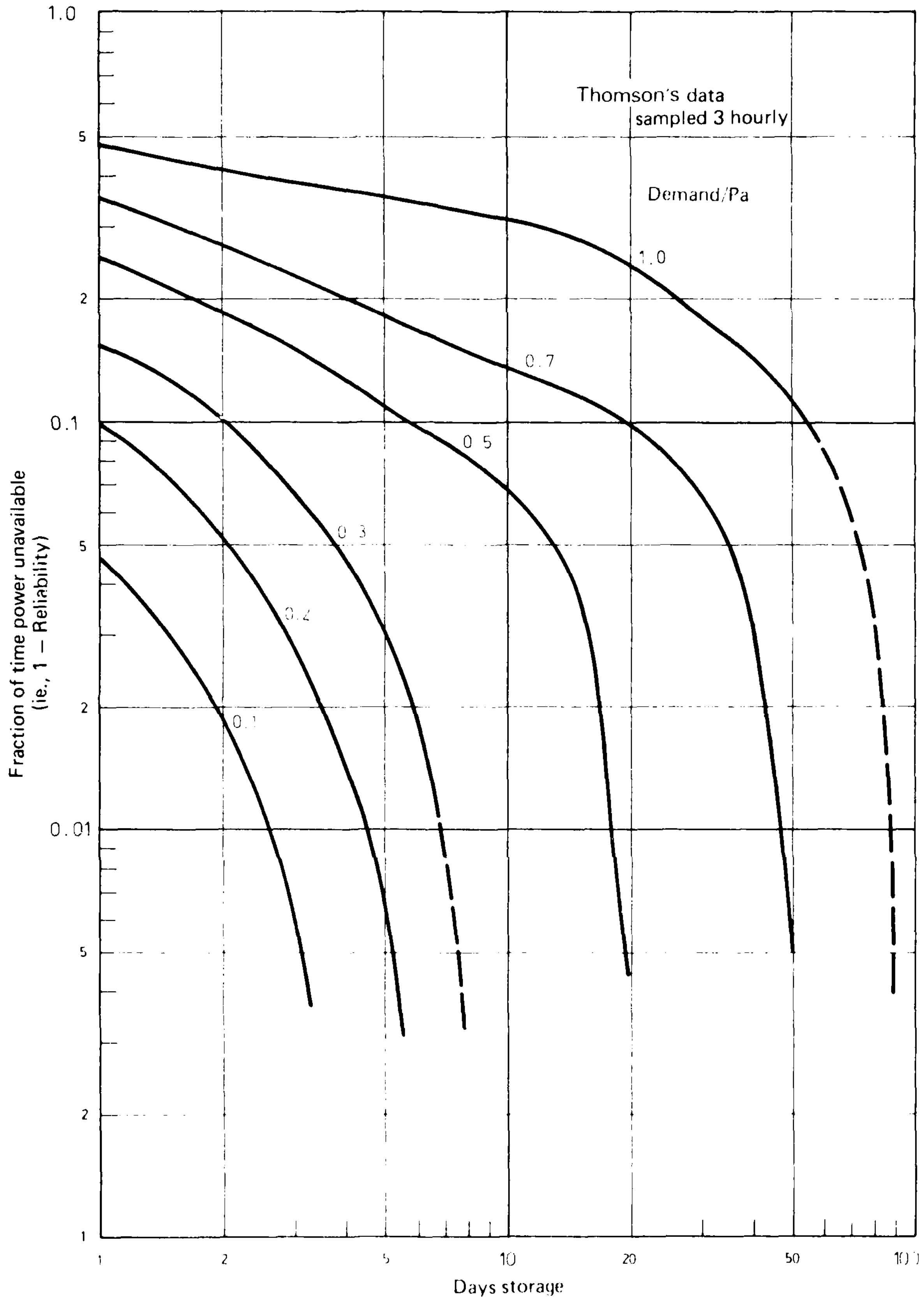

FIG 7b: RELIABILITY OF WIND POWER SYSTEMS WITH VARIOUS LOADS AND STORAGE CAPACITIES, CALCULATED USING ARL WIND SPEED DATA AVERAGED OVER 6 MINUTES AND SAMPLED AT 3 HOURLY INTERVALS.

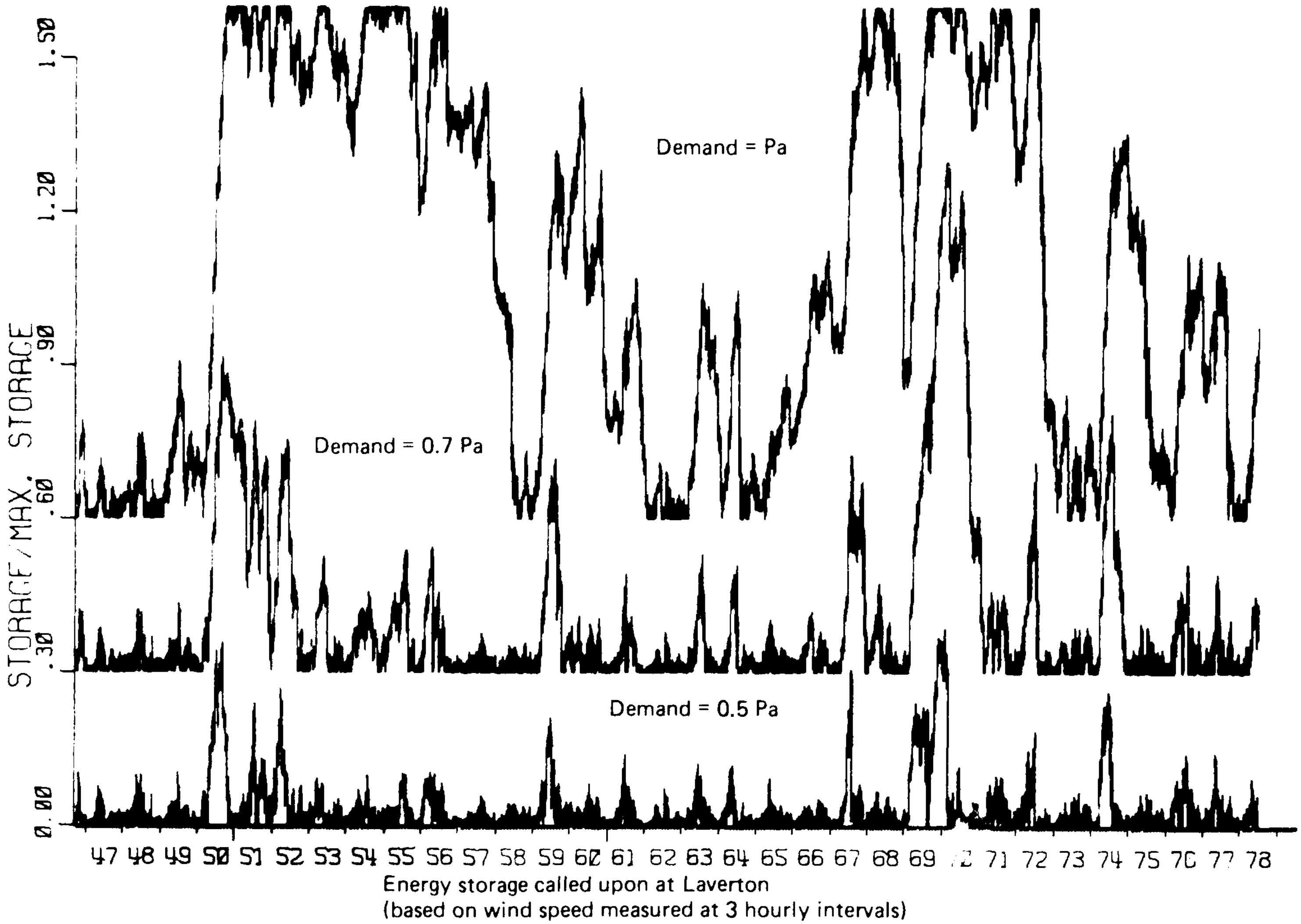

FIG 8a: VARIATION OF ENERGY STORAGE CALLED UPON WITH TIME. CALCULATED USING 3-HOURLY SAMPLES OF LAVERTON WIND SPEED DATA.

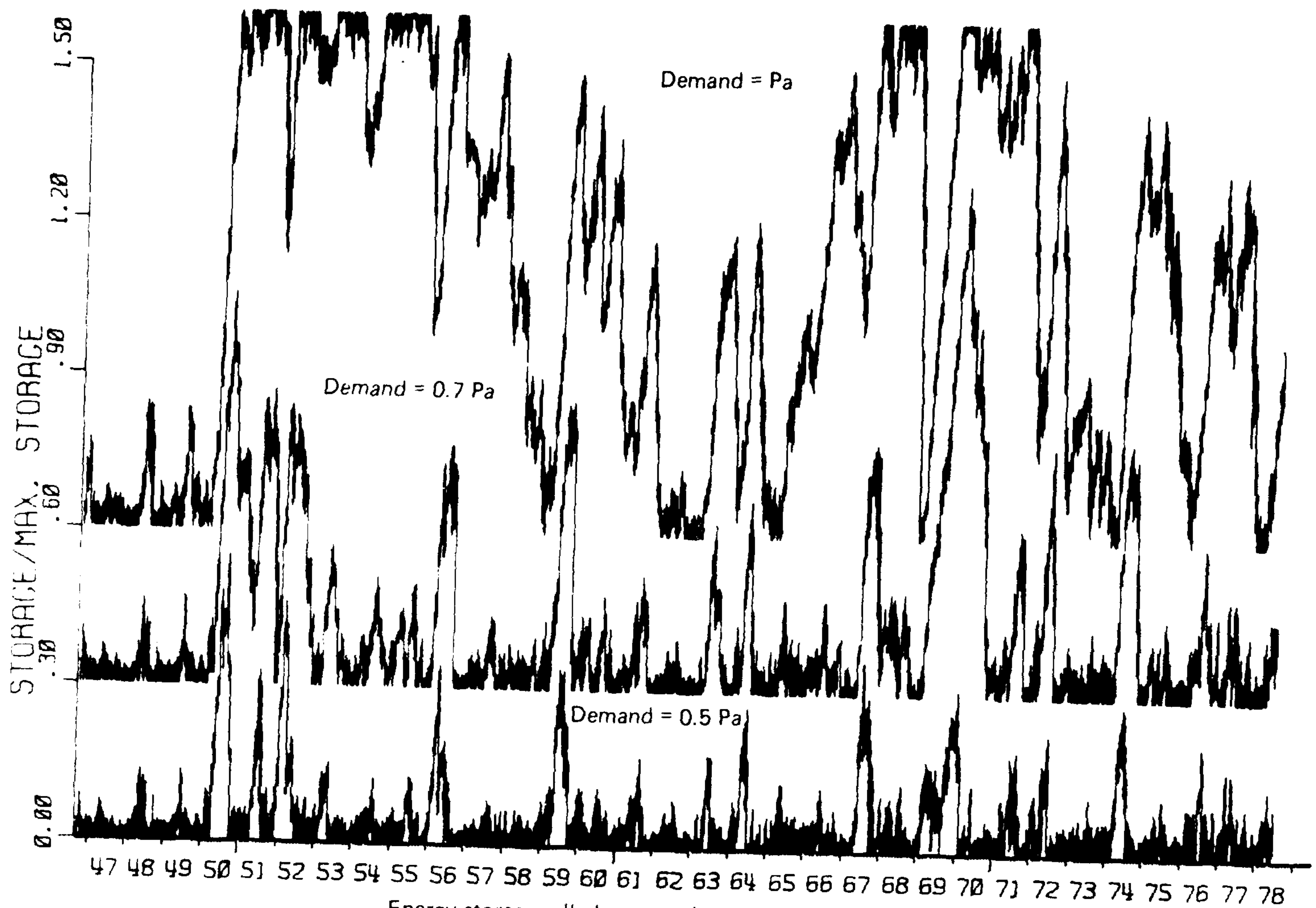

FIG 8b: VARIATION OF ENERGY STORAGE CALLED UPON WITH TIME. CALCULATED USING DAILY 9am SAMPLES OF LAVERTON WIND SPEED DATA.

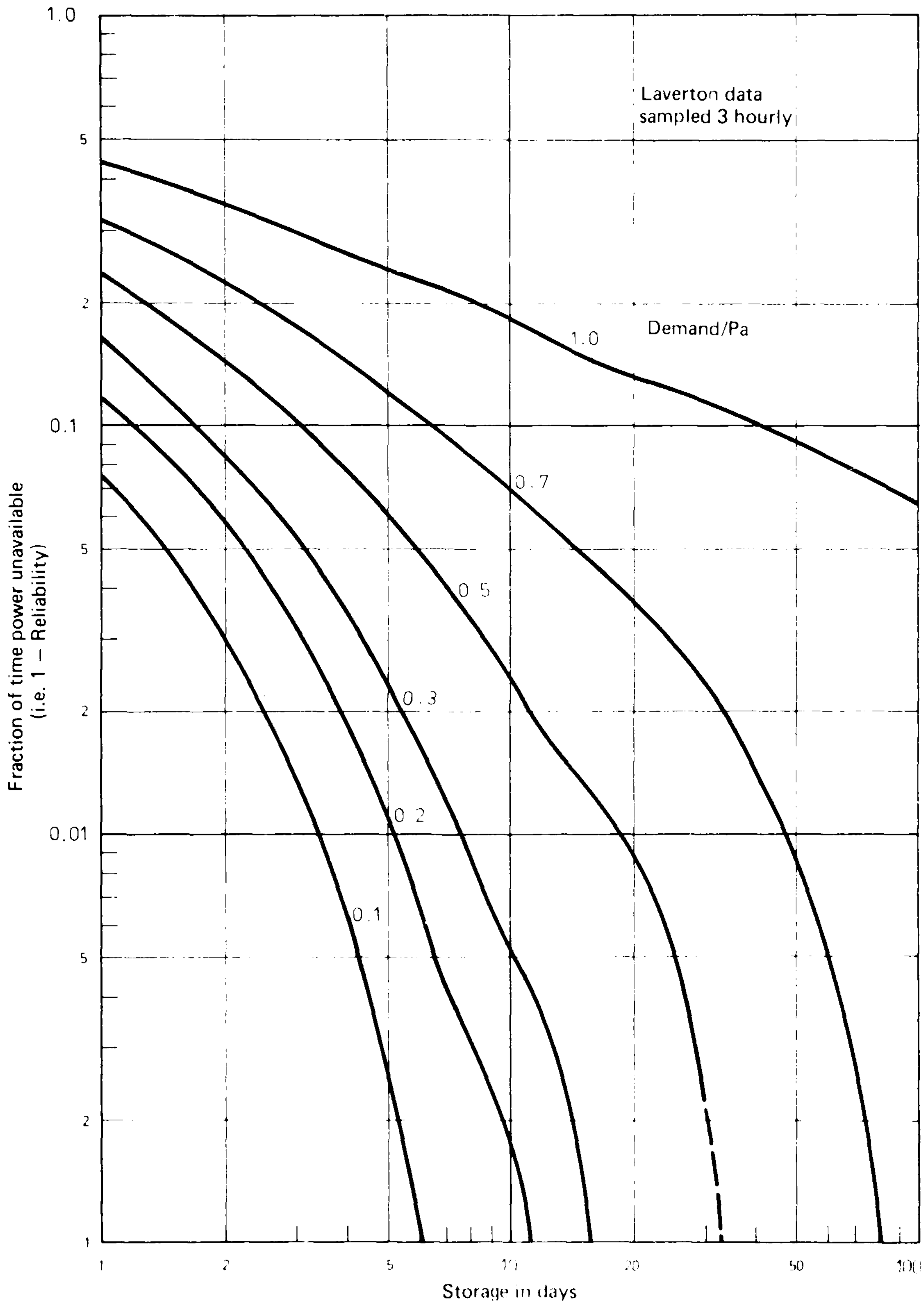

FIG 9a: RELIABILITY OF WIND POWER SYSTEMS WITH VARIOUS LOADS AND STORAGE CAPACITIES, CALCULATED USING 3 HOURLY SAMPLES OF LAVERTON WIND SPEED DATA.

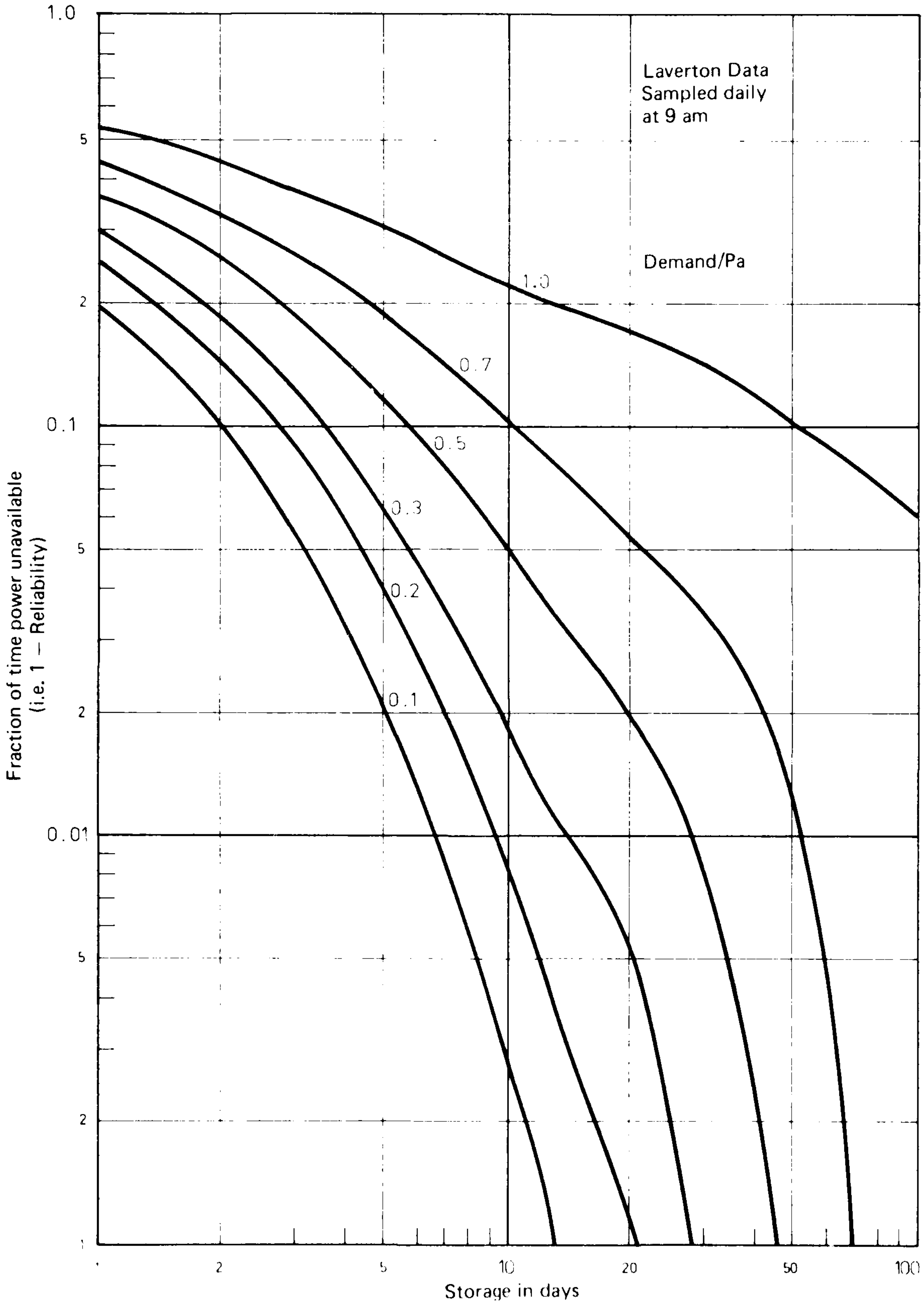

FIG 9b: RELIABILITY OF WIND POWER SYSTEMS WITH VARIOUS LOADS AND STORAGE CAPACITIES, CALCULATED USING DAILY 9 AM SAMPLES OF LAVERTON WIND SPEED DATA.

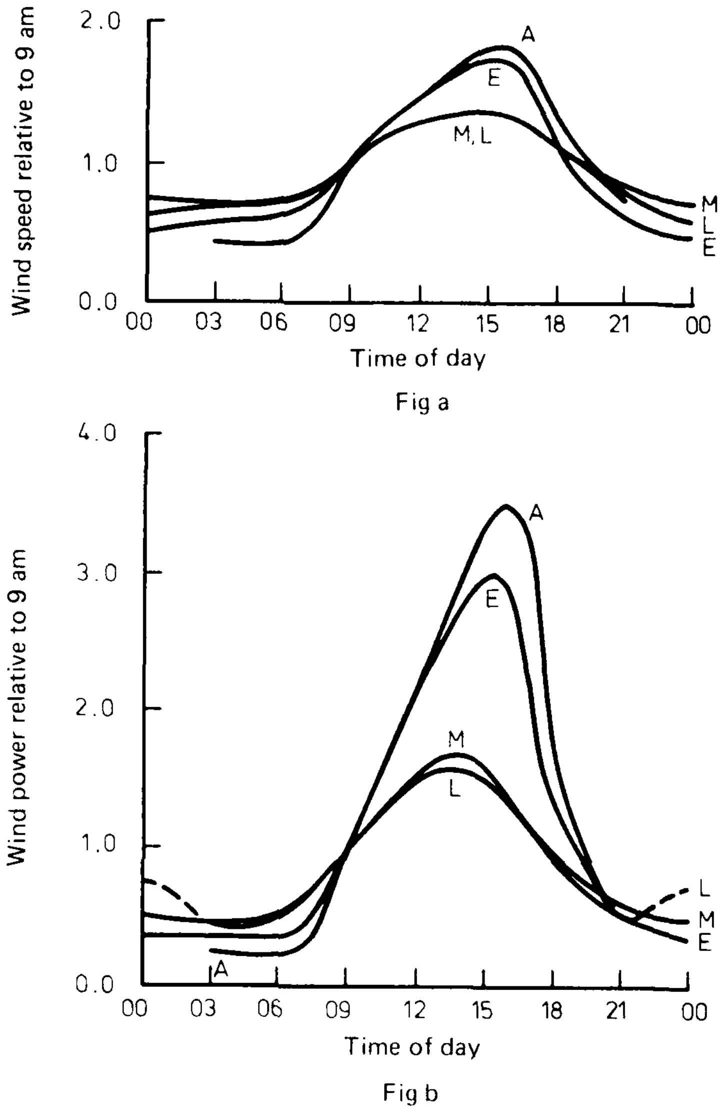

FIG 10: DIURNAL VARIATION OF WIND SPEED AND WIND POWER AT ARCHERFIELD(A), EAGLE FARM(E), MELBOURNE REGIONAL OFFICE(M), AND LAVERTON(L).

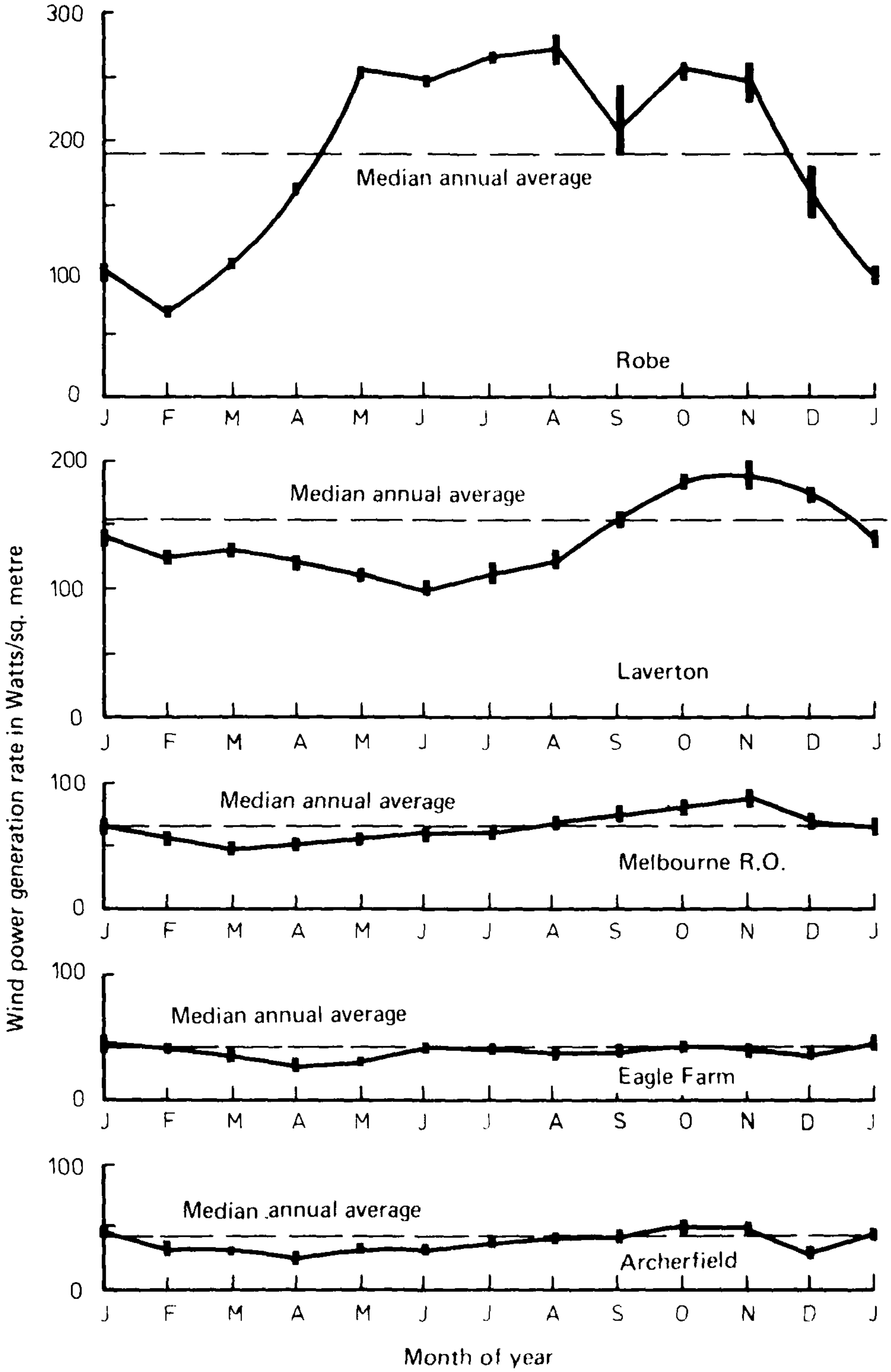

FIG 11: SEASONAL VARIATION OF WIND POWER AT VARIOUS STATIONS – MEDIAN VALUES OF MONTHLY AVERAGE WIND POWER GENERATION RATE AT 9AM.

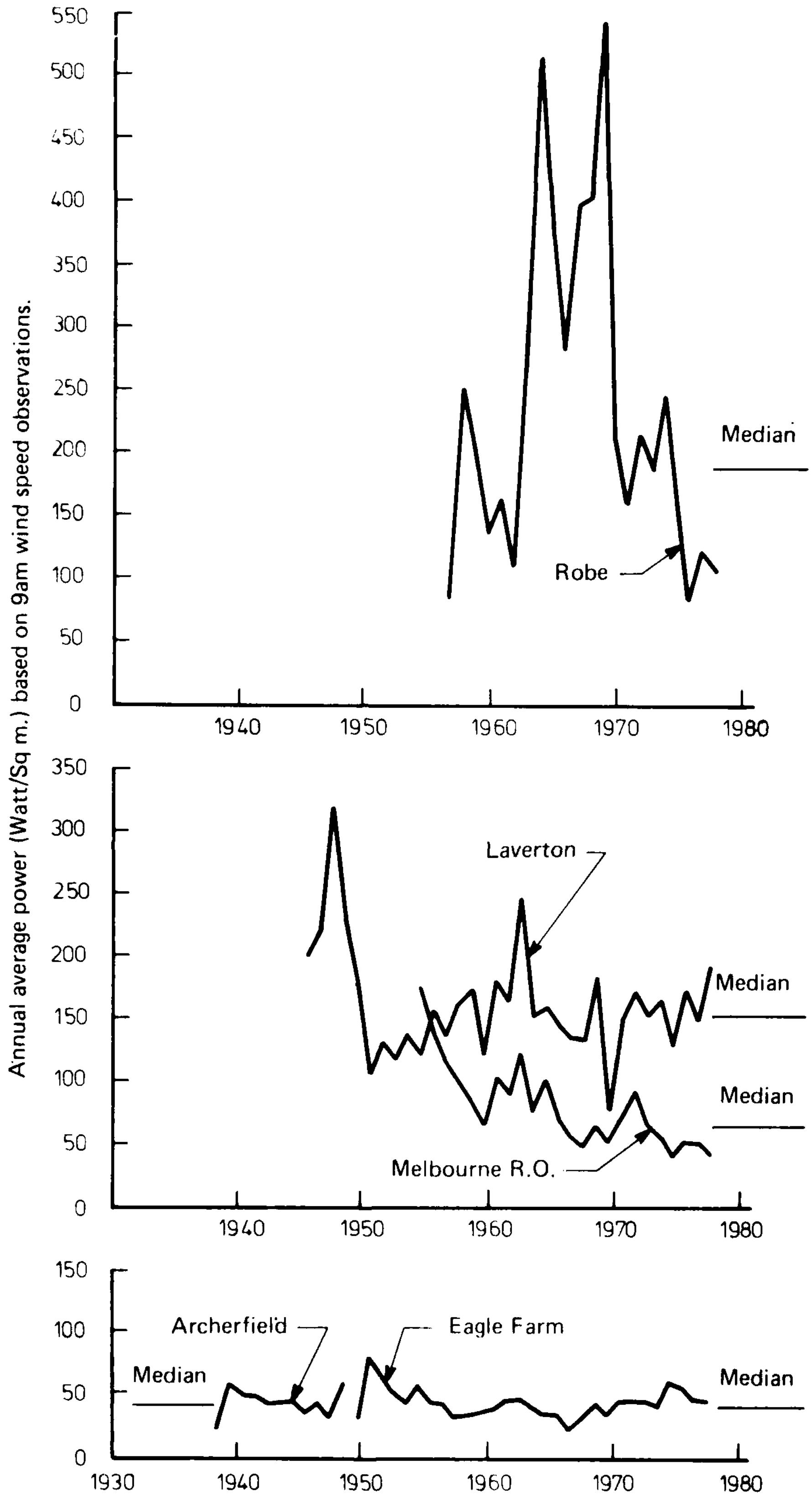

FIG 12: VARIATION OF ANNUAL AVERAGE POWER GENERATION RATE AT VARIOUS STATIONS.

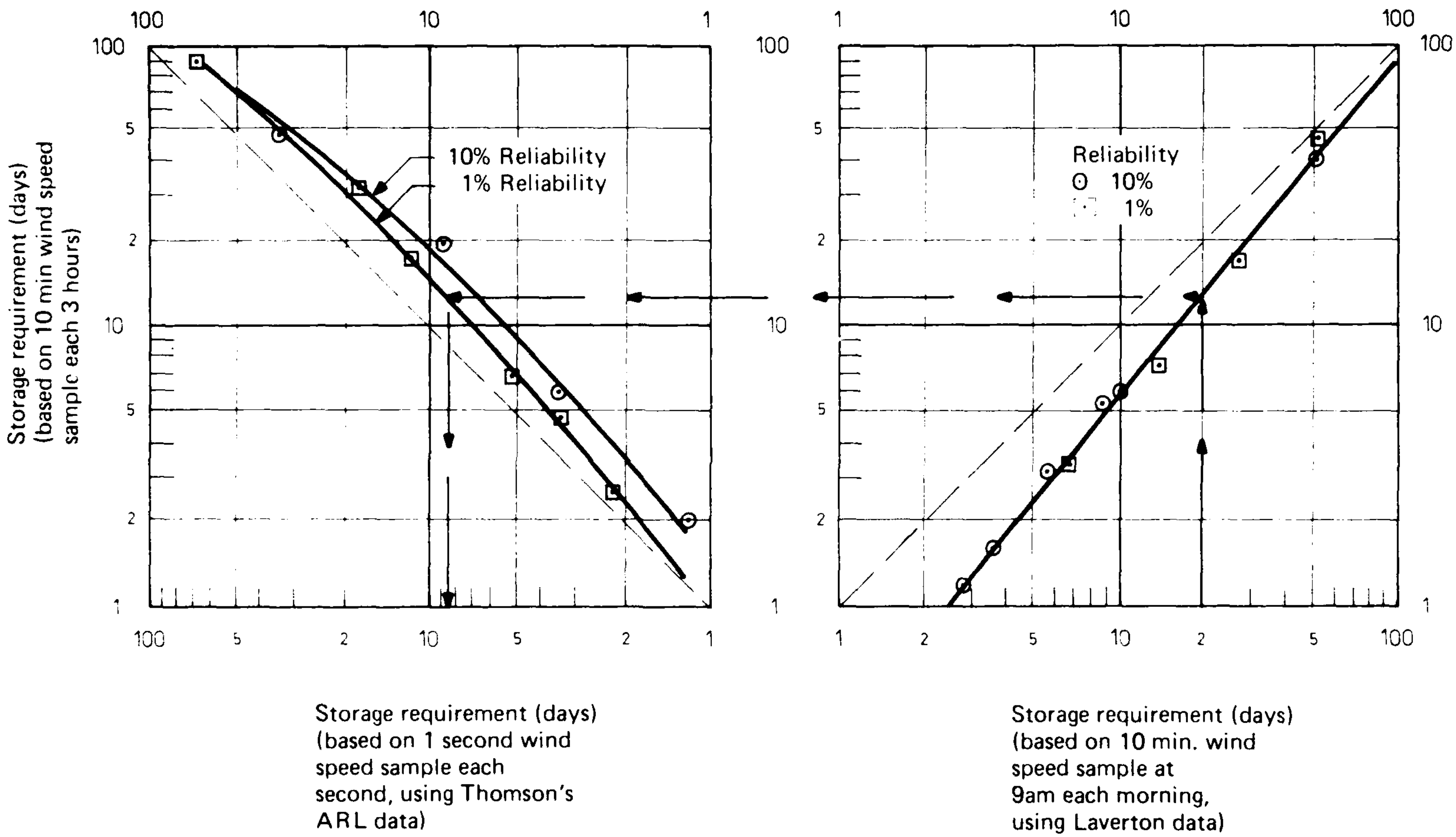

FIG 13: EFFECT OF VARIOUS WIND SPEED SAMPLING INTERVALS ON CALCULATED ENERGY STORAGE REQUIREMENT FOR A WIND POWER SYSTEM.

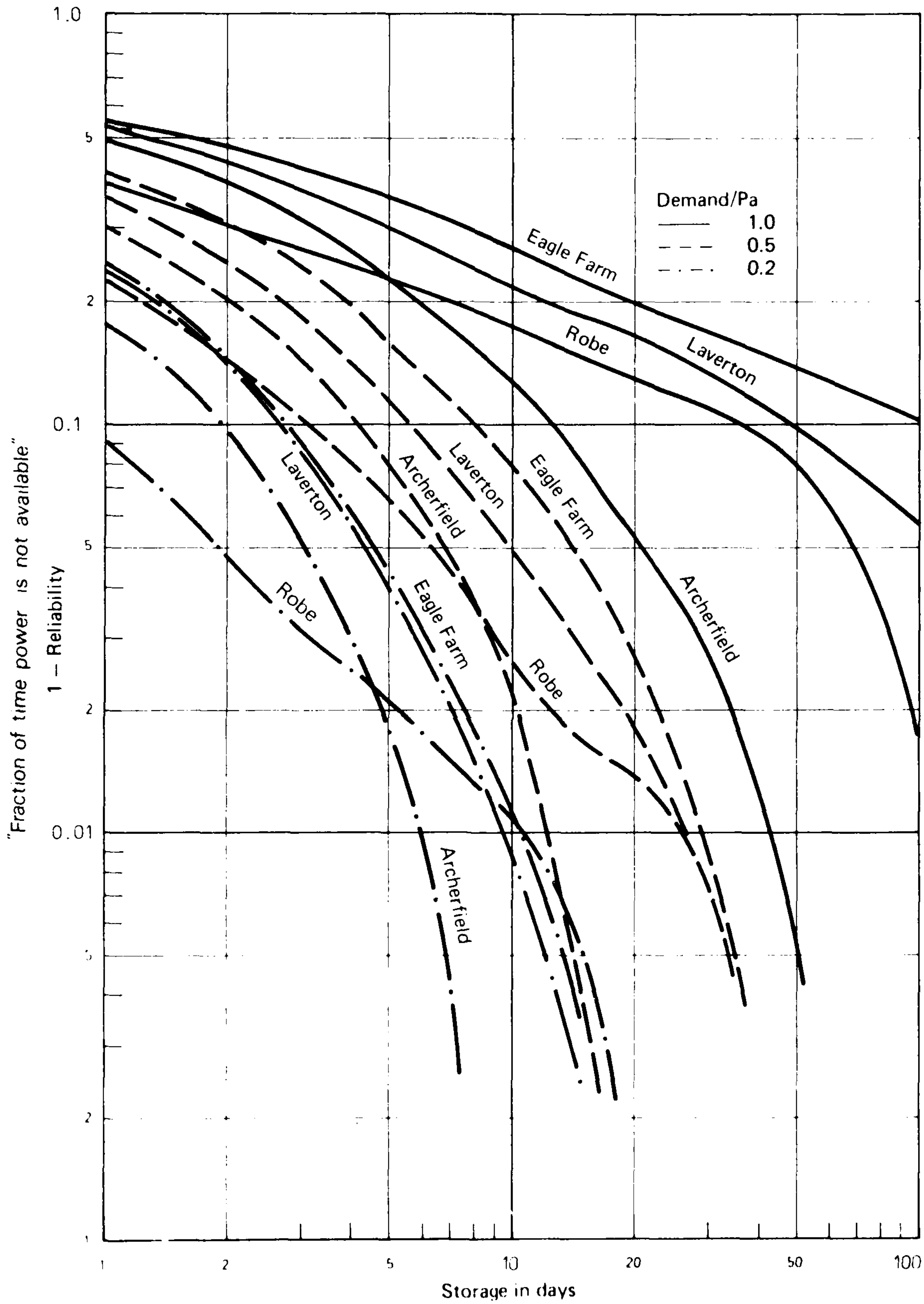

FIG 14: COMPARISON OF RELIABILITY DIAGRAMS FOR WIND ENERGY SYSTEM DESIGN AT VARIOUS STATIONS.

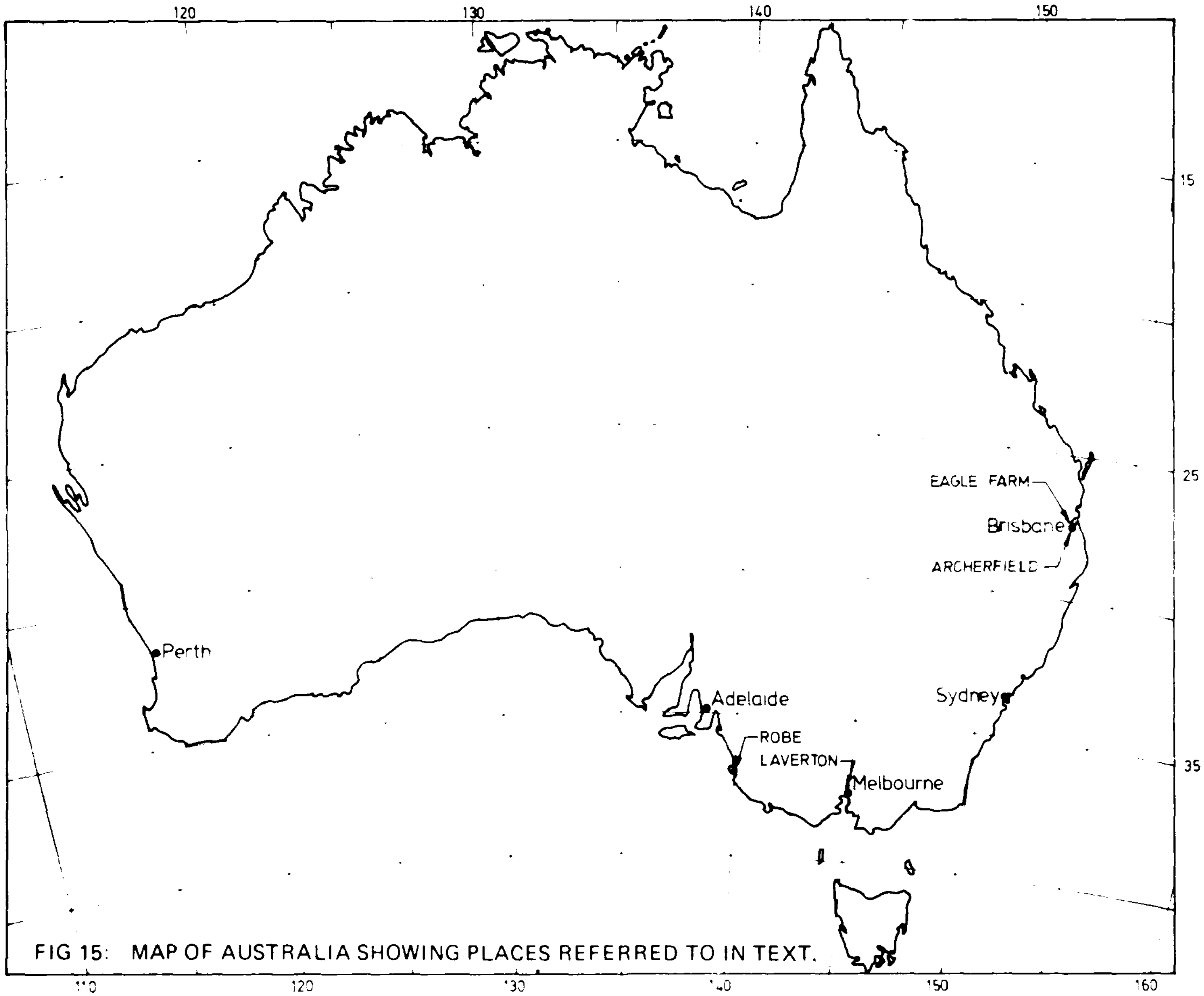

FIG 15: MAP OF AUSTRALIA SHOWING PLACES REFERRED TO IN TEXT.

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